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Impact of large amounts of wind power on the operation of an electricity generation system: Belgian case study

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A B S T R A C T

Wind power can have considerable impacts on the operation of electricity generation systems. Energy from wind power replaces other forms of electricity generation, thereby lowering overall fuel costs and greenhouse gas (GHG) emissions. However, the intermittency of wind power, reflected in its variability and relative unpredictability restrains the full potential benefits of wind power. The variable nature of wind power requires power plants to be ready for bridging moments of low wind power output. The occurrence of forecast errors for wind speed necessitates sufficient reserve capacity in the system, which cannot be used for other useful purposes. These forecast errors inevitably cause efficiency losses in the operation of the system. To analyse the extent of these impacts, the Belgian electricity generation system is taken as a case and investigated on different aspects such as technical limitations for wind power integration and cost and GHG emissions' reduction potential of wind power under different circumstances.

Contents

1. Introduction

The objective of this paper is to get a deeper insight in the impact of wind power on the operation of an electricity generation system. The focus is put on the interaction with a functioning power system, as opposed to investigating hybrid systems with

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wind power [1–3]. The approach is to consider the system without the inclusion of a grid, thereby focusing on the generation units and their technical characteristics.

The power plants integrated in an electricity generation system are both electricity generators and providers of technical balancing. No single power plant stands on its own. The inclusion of power plants in an electricity generation system ensures a better electricity delivery. Power plants operated in a system can cover problems incurred with other plants in the system. In what follows, the operation of the system and the application of conventional power plants to accommodate the technical integration of wind power are investigated. The integration of new units, in this instance wind turbines, has consequences on the entirety of the system [4–16]. Operational rules and corresponding costs might change due to adaptations to the system. The different impacts of wind power are investigated in the following sections.

Firstly, the employed methodology is explained. The principles on how a model simulates the Belgian electricity generation system are described in detail. Next, as a first analysis, a single operator-generator is considered. The system modelled corresponds to the Belgian system, chosen for its diverse generation mix. The grid constraints and potential bottlenecks are not included in the study and there are no exchanges with neighbouring systems. This is a reasonable assumption when only considering the control zone of the Belgian Transmission System Operator (TSO) Elia and a limited amount of wind power. All available power plants are used in a cost-optimal way to cover demand in the Belgian control area. The costs and greenhouse gas (GHG) emissions' reduction potential of different amounts of wind power in the system are analysed. The impact of wind power on these parameters is examined in Section 3. In the last section the boundaries in the introduction of large amounts of wind power into the Belgian system are explored. On the short-term, the available power plants can become inadequate or too costly to compensate for the fluctuating wind power output. On the long-term, with changes in the system and rising demand, additional power plants, apart from wind turbines might be needed.

2. Methodology

To consider the costs and GHG emissions' impact and technical limits for wind power in Belgium, both a long- and short-term approach can be adopted, in accordance with the definition of the reliability of an electricity generation system [17–19]. On the long-term, the technical limits are determined by the adequacy of the Belgian electricity generation system and on how this system needs to be defined to successfully integrate large amounts of wind power. On the short-term, large amounts of electricity from wind power will impact the operation of the system.

On the long-term, an electricity generation system has to be built so as to attain the desired level of reliability under a wide set of situations. Investments in the system might be necessary to cope with changes, such as the addition of wind power or an increase in demand. If the system is foreseen not to be sufficiently adequate, new investments in power plants can prove to be a solution. Therefore the technical limits of wind power need to be seen in the context of maintaining reliability. With unchanged demand, addition of wind power would probably not lead to lower adequacy. However, in the light of increasing demand, an investment in a certain amount of wind power does not provide the same contribution to system reliability as a conventional power plant. This can also be considered as a technical limit for wind power in the electricity generation systems.

On the short-term, based on the operation of the electricity generation system but without considering its grid, wind power introduction turns out to be limited by the operation of the system. The composition of the Belgian system and the operational characteristics of the constituent power plants exert an important influence on the integration of wind power.

This paper focuses on the short-term impact of wind power on cost and GHG emissions' reduction and on the technical boundaries of the system integrating increasing amounts of wind power. To learn more about these influences, simulations of the Belgian system are performed with increasing installed wind power capacity.

For the simulation of the Belgian system, a mixed integer linear programming (MILP) approach is adopted, as also used in [20]. The cases are modelled as optimisation problems under cost minimisation for 24-h timespans.[1] The model optimises the unknown variables such as activation level of power plants and production quantities using this objective function. Typical non-convexities such as startup costs, minimum operating points and minimum up- and down-times are taken into account. The problem is solved by the commercial MILP solver Cplex within the GAMS environment [21,22]. A model simulating the operation of an electricity generation system allows for an accurate reproduction of the elements that come into play, more specifically when integrating wind power in the system. On the one hand, the fluctuating wind speed profiles illustrate the variability over time. On the other hand, to illustrate the unpredictability or uncertainty of wind power, a distinction is made between a Unit Commitment (UC) phase, based on forecasted data, at the start of the 24-h period and a dispatch phase for every hour based on the actual wind power output. Discrepancies between forecast and actual output, defining the wind's unpredictability, need to be addressed by the available power plants, which depend on the choices made during UC.

The model takes all the relevant operational characteristics of an electricity generation system into account. For the exercise dealt with in this paper, mainly the power plant characteristics, such as ramp rates, spinning reserves, the use of pumped hydro storage stations [23] and fuel usage are of importance. The fuel prices are based on the International Energy Agency (IEA) World Outlook prices of 2005 [24]. In terms of fuel costs coal-power plants come second in the merit order after nuclear plants.[2] Gas-fired power plants, especially the efficient CC power plants, are also used extensively due to their flexible operating characteristics. Smaller gas turbines and diesel motors fill up temporal needs and offer additional flexibility to the system.

To analyse different aspects of wind power integration in Belgium, four different wind speed profiles are chosen to represent typical patterns in wind power output during a day. They are based upon actual data from the Belgian Meteorological Institute [25]. Wind power is typically a variable energy source, which becomes clear when looking at wind speed profiles. The profiles that are applied in the MILP model, depicted in Fig. 1 and also used in [26–28], represent the fluctuating behaviour of wind. The transformation from wind speed to wind power is based on the Vestas V80 wind turbine power curve, as shown in Fig. 2 [29]. In the simulations, the wind power fluctuation has to be dealt with using the available power plants in the system.

Besides applying different wind profiles, different demand profiles are being looked at too. These are shown in Fig. 3 and are taken from actual 2006 demand data from Elia, the Belgian transmission system operator (TSO) [30]. They are chosen to represent distinct demand situations and have been used also in other studies [20,26–28,31].

[1] This model has been developed at the division of TME, KULeuven.

[2] The used IEA prices mention a crude oil price around 36 $/barrel, where it has risen to above 100 $/barrel in 2008. However, the actual prices are of less importance than the ratio between them. The focus is not so much on the overall fuel cost than on the effects of the use of different fuels.

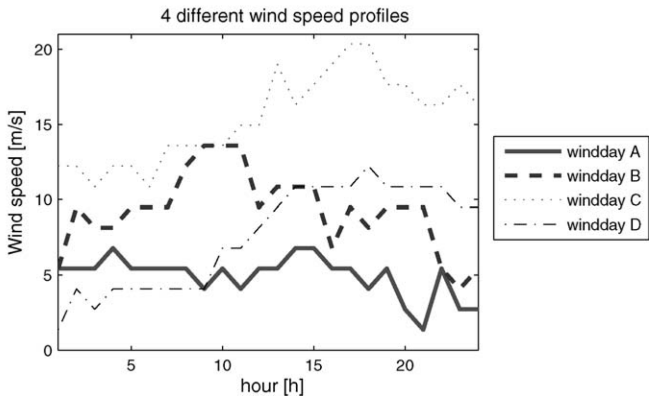

Fig. 1. Wind speed profiles of 4 different days, showing typical fluctuations [25].

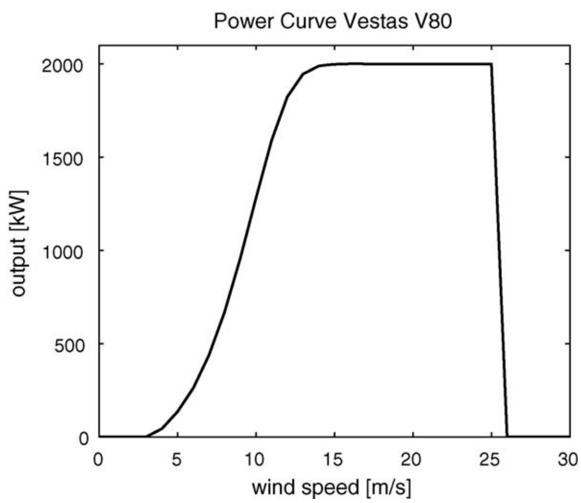

Fig. 2. Power curve for the Vestas V80 2 MW wind turbine. [29].

To evaluate the integration of wind power in Belgium, the demand and wind speed profiles of Figs. 1 and 3 are adopted for increasing amounts of wind power. In steps of 500 MW, wind power installations of up to 4500 MW are investigated. Two points of view are considered in simulating the introduction of increasing amounts of wind power. Firstly, a perfect forecast of wind speed is used. Secondly, a certain forecast error is applied to the wind speed. In this second analysis, the option of curtailing wind power

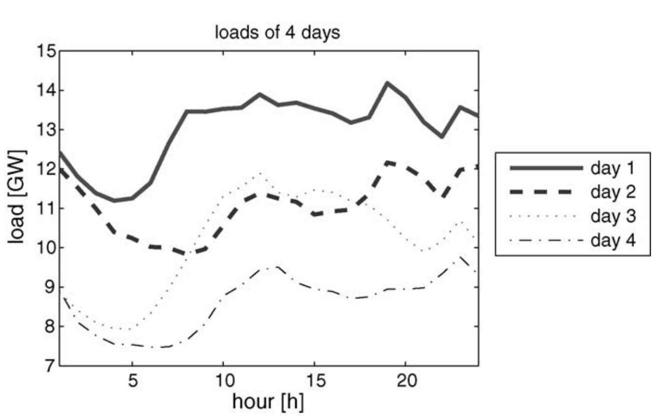

Fig. 3. Demand profiles of 4 different days based on actual 2006 demand data of Elia [30].

is investigated as well. This is important to consider since at this stage, no export of excess wind power output is foreseen.

3. Impact of wind power on costs and emissions

The actual impact of wind power in Belgium can be expressed in several ways. Two are discussed in what follows, namely the impact of wind power on operational cost and on GHG emissions. They both illustrate the benefits wind power has on the system. Also the effect of a GHG emissions tax is discussed.

3.1. Operational cost of wind power in Belgium

In a first analysis, the pure impact of wind power introduction on the operational cost is considered. Therefore, a perfect forecast of wind speed is assumed to only take the fuel and operational aspects into account. In a second phase, both negative and positive wind speed forecasts are evaluated to specifically focus on the cost of erroneous forecasts. Both the negative and positive forecast errors on wind speed reduce the cost saving potential of wind power. A negative forecast error refers to a situation where the forecasted wind speed turns out to be an underestimation of the actual wind speed. A positive forecast error is to be interpreted as an overestimation of the wind speed. The degree to which cost savings are accounted for is analysed in this section.

3.1.1. Cost reduction potential of wind power with perfect forecast

When the actual wind power output is perfectly known during the UC period, the operation of the system experiences practically no hinder from the wind power integration. The power plants can be switched on and off according to the most optimal schedule so that supply and demand are balanced at all times.

When looking at the results in Fig. 4, it is obvious that the demand profiles considerably influence the extent of operational cost savings that can be achieved by wind power. This has to do with the usage of the available power plants in the system. Power plants are ranked according to a merit order, with the cheapest electricity production options coming first, up to the most expensive power plant [32,33]. This merit order lies at the basis of the unit commitment of the power plants. Therefore, at any given time, it is logical to see that higher levels of demand correspond to the activation of increasingly expensive power plants. The last power plant that is activated to meet the last MWh of demand can be referred to as the marginal power plant. This is visualised in Fig. 5. High demand profiles will see more expensive marginal plants on the whole. This leads to more expensive power plants being outperformed by electricity from wind power, since the marginal plant is the first to be replaced when cheaper options become available. That is why the higher demand profiles see larger operational cost savings from the generation of energy from wind power.

When looking closely at Fig. 5, it is clear that *Day 1* has more expensive power plants activated than *Day 4*. When the same amount of wind energy is delivered in both systems, *Day 1* logically undergoes the highest operational cost saving. The difference is so high that *Day 1* shows cost savings twice as high as *Day 4*.

As long as the marginal power plant remains the same while being replaced by increasing amounts of wind energy, the cost reduction is linear. When the marginal power plant changes, in this case to a less expensive power plant, the cost reduction curve will become less steep.

3.1.2. Cost reduction potential of wind power with negative forecast errors

To look into the impact of negative wind speed forecasts on the cost saving potential, the method of wind power integration with

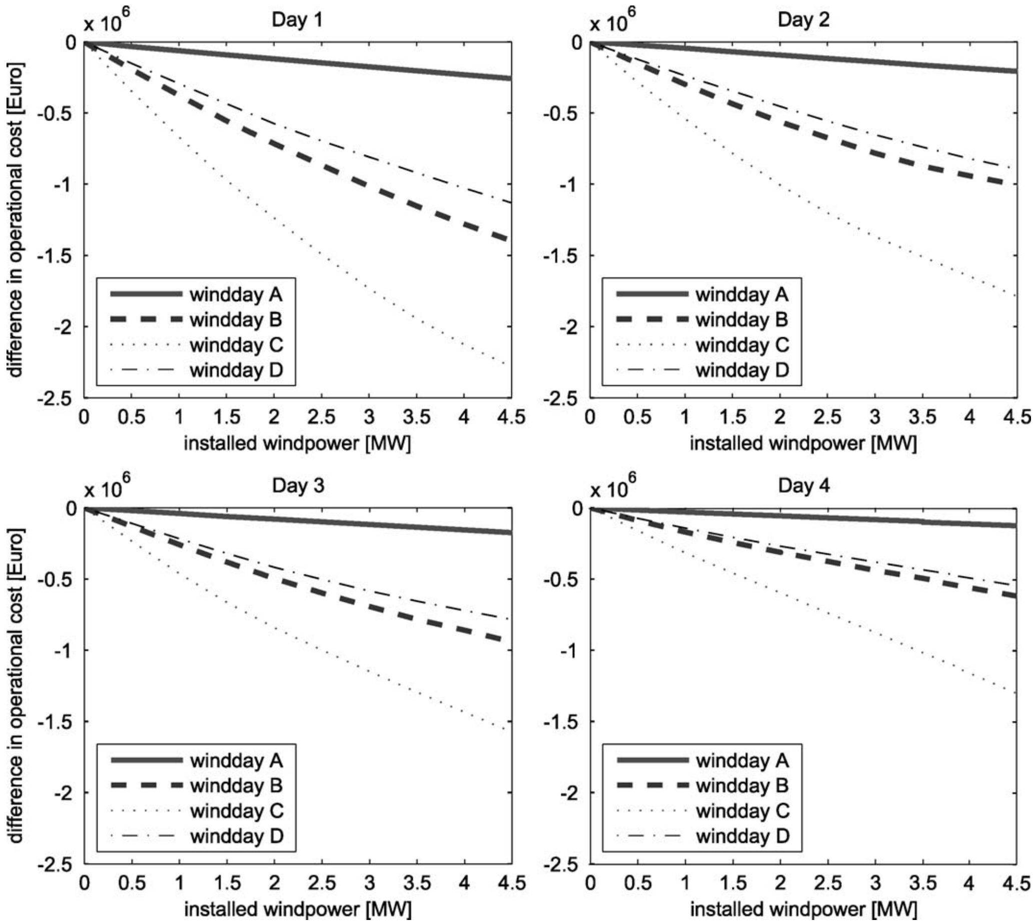

Fig. 4. The cost savings for 4 different decreasing demand profiles, *Days 1–4*, each showing the impact of the 4 chosen wind speed profiles for increasing amounts of installed wind power in the Belgian system. The operational cost savings relate to a situation without any wind power in the system and are expressed as negative costs.

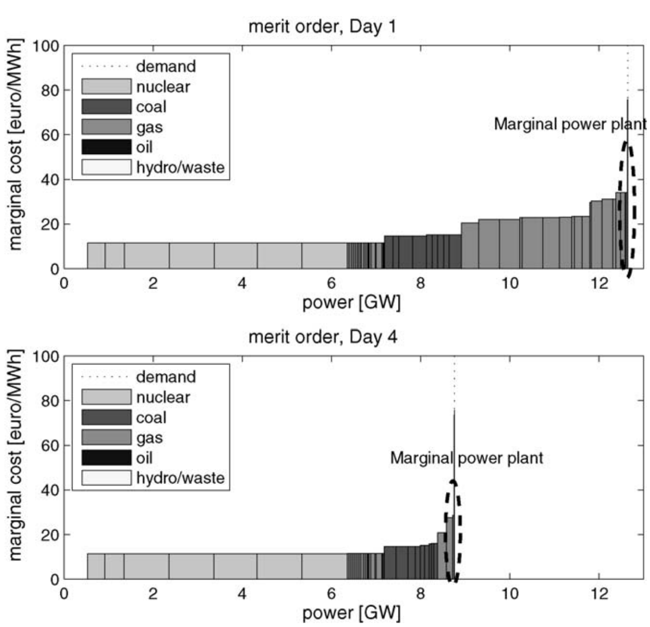

Fig. 5. Merit order with marginal power plant for *Day 1*, with a high inelastic demand and *Day 4*, with a low inelastic demand, both at 6 pm and without installed wind power.

curtailment is used.[3] This allows evaluating both the impact of energy lost to curtailment and of having to readjust the operation due to the unexpected changes.

The combined fact of having to curtail wind power and operating the system under uncertainty leads to suboptimal solutions. The negative forecast error leads to additional costs in the system when compared to the situation without any forecast error. These are illustrated in Fig. 6 for a negative forecast error of 2 m/s. The results of Fig. 6 represent the costs of erroneous negative forecasts as percentages of the cost savings obtained by introducing wind power under perfect forecast, as illustrated in Fig. 4. It gives the loss in operational cost reduction compared to a situation with perfect forecast of wind speed. These losses can amount to up to 30% of the total amount of cost reduction that can be obtained with perfect forecast of wind power. This means that about a third of potential cost savings through fuel saving can be lost to measures taken to cope with the forecast error.

The low demand profiles, that benefit the least from the wind power integration, also experience most difficulties and corresponding costs when a negative forecast error takes place. This leads to the conclusion that, especially with considerable errors in wind speed forecast, the lower demand profiles see the least benefit in terms of cost reduction through wind as a 'free fuel'.

[3] Curtailment refers to wind power output being shed. The impact of curtailment on system operation is further discussed in Section 4.3.2.

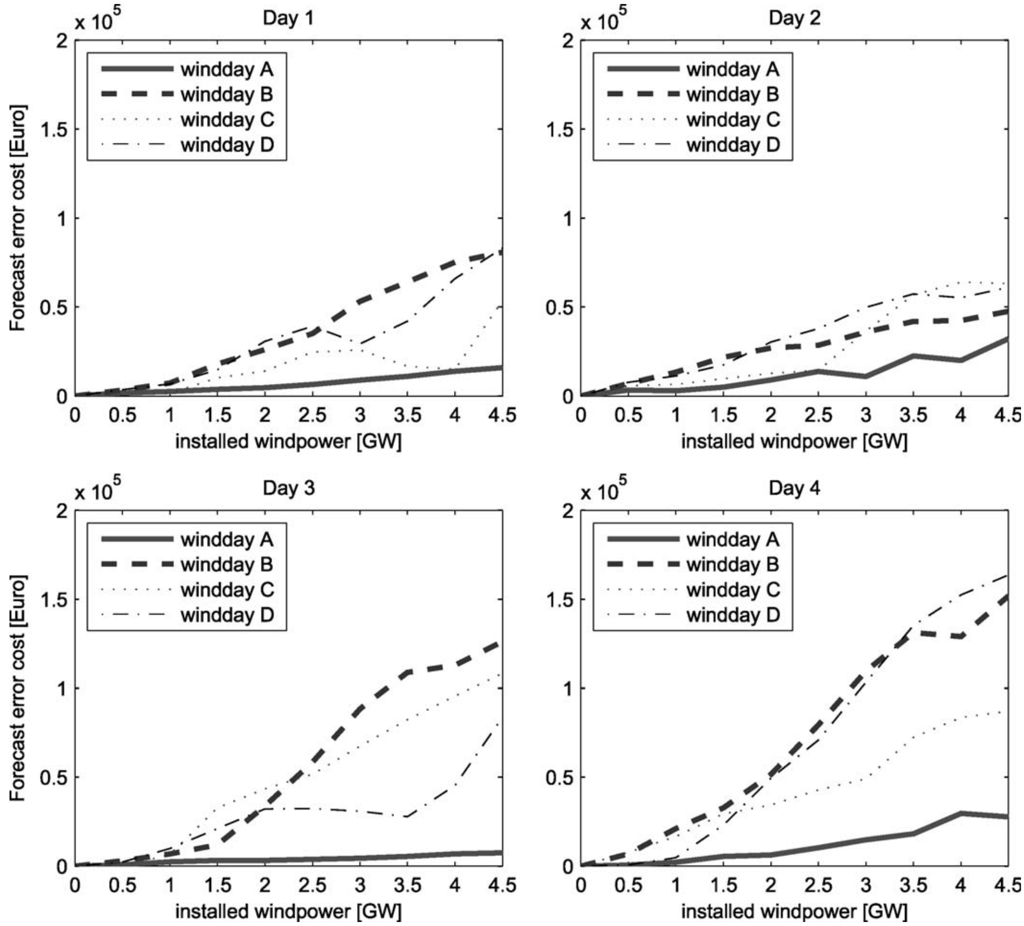

Fig. 6. Forecast error cost expressed as the difference between a situation with a negative forecast error of 2 m/s and a situation without any forecast error. For the demand profiles *Days 1–4* with increasing amounts of wind power and wind speed profiles *Windday 1–4*.

In general, Fig. 6 shows that significant additional costs arise for negative forecast errors. When a system is not expecting additional electricity generation, it will have to adapt on a short time frame, which inevitably leads to increasing costs. This stresses the importance of having quality forecasts on the one hand and adequate options to cope with uncertainty on the other hand. Extensive balancing options, such as using a pumped hydro storage station or grid interconnection are good examples of the latter. What certainly needs to be avoided for efficient integration of wind power into an electricity generation system is the excessive loss of energy due to curtailment. The values of lost cost reduction potential in Fig. 6 clearly prove this.

3.1.3. Cost reduction potential of wind power with positive forecast errors

Positive forecast errors, where the wind speed forecast is higher than the actual wind speed and where additional power has to be found to close the gap between the forecast and the reality, occur as well. Not only do they bring technical barriers to the integration of wind power in the system, as will be discussed in Section 4.2, but also do they lead to efficiency loss and ensuing additional forecast error costs. The evolution of the costs related to the positive forecast error of 2 m/s is represented in Fig. 7. Only the ranges that could be covered with the system's available generation units are represented. The circles in Fig. 7 indicate where the system cannot cope with larger amounts of installed wind power capacity anymore.

It is clear that the forecast error still constitutes a considerable cost, comparable to the forecast error costs obtained with a negative forecast error. In the occurrence of low demand profiles combined with large amounts of installed wind power, significantly large shares of the fuel saving gains of wind power are counteracted. By comparing Figs. 4 and 7, this can be illustrated with the case of the wind speed profile *Windday A*. The costs resulting from the forecast error for the combination of *Windday A* and the demand profile of *Day 4* with 4500 MW of installed power, are completely nullifying the cost benefits of having wind power as a free energy source. Also for other combinations of demand and wind speed profiles, the cost reduction benefit is considerably offset by the forecast error.

A remarkable fact of the first three demand profiles, most in particular for *Day 1*, is the steep rise in additional operational cost due to the forecast error for the first 500 MW that is being considered. The reason is to be found in fewer gas-fired combined cycle power plants being available in the system when only 500 MW of wind is installed. Therefore, less efficient classic single turbine power plants are used more extensively for both firm generation and reserve provision. With the given forecast errors, these relatively expensive reserves are also called upon to compensate for the deficiency in generation. With higher wind power capacity such as 3500 MW, the system is somewhat relieved in terms of generation capacity. Some combined cycle power plants are still available to use as reserves. Although more reserves are eventually needed for a 2 m/s forecast error in the 3500 MW scenario, the available cheaper and more flexible power compensates for it. Another reason for the forecast error to have less impact on the 3500 MW scenario is to be found in the decrease in reliability of the system. Although the 3500 MW scenario uses

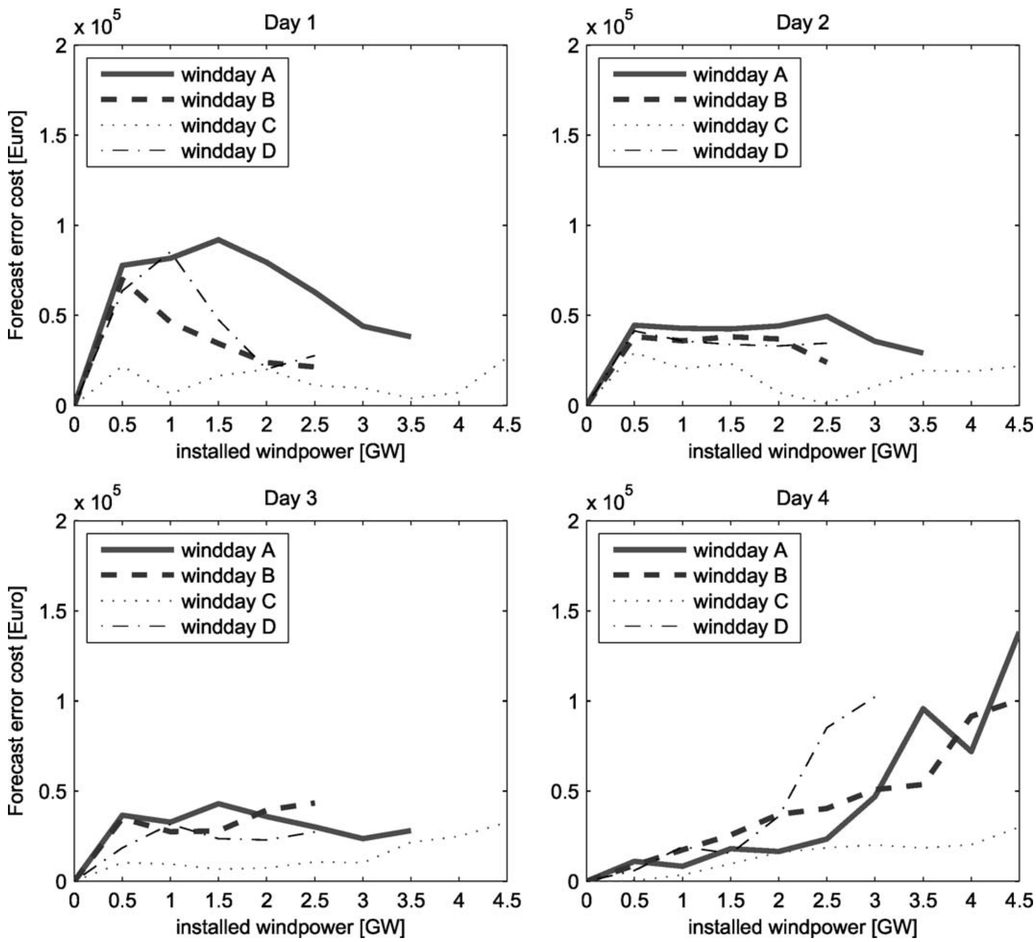

Fig. 7. Forecast error cost expressed as the difference between a situation with a positive forecast error of 2 m/s and a situation without any forecast error. For the demand profiles *Days 1–4* with increasing amounts of wind power and with wind speed profiles *Windday 1–4*.

cheaper reserves, it does not have enough to cover the total reserve requirements. This leads to lower reserve-related costs but inevitably has adverse effects on system reliability parameters such as the LOLE.

3.2. Greenhouse gas emissions effect

Wind power has as one of the main advantages that it is emission-free. This translates itself in considerable reductions in greenhouse gas (GHG) emissions for large amounts of wind energy. These large amounts of wind energy occur with high levels of installed wind power and wind speed levels that allow for good usage of the wind turbines. This joint effect can be witnessed in Fig. 8, where reductions of up to 60% compared to a situation without any wind power are reached for a situation with perfect forecast of the wind speed.

The impact of wind power on GHG emissions is different from the one on operational cost. Since in the case described in Figs. 4 and 5 above, the marginal power plant consists of gas-fired power plants, the GHG reduction curve will suddenly become steeper as soon as the switch takes place from a gas-fired to a coal-fired power plant. Coal-fired power plants are significantly more polluting than gas-fired plants. Therefore, whenever an amount of wind energy outperforms coal-based electricity generation, the GHG reduction effect will be significant. This effect can be observed in Fig. 8, where, for example on Day 1 with Windday C, a steeper decline in GHG emissions can be observed from 3000 MW of installed wind power on. The steeper decrease in emissions for the same wind speed profile on *Day 2*, occurs at a lower wind power level, namely 1500 MW. This is due to the lower overall demand of *Day 2*, leading to the coal-power plants becoming the marginal plant with increasing installed wind power capacity sooner than during *Day 1*. *Day 2* also shows increases in relative emissions at the end of the scope of installed wind power. With such levels of installed wind power, considerable adaptations occur in the system operation to be able to process the massive drop and increased fluctuations in residual demand. By absorbing all the produced wind energy, shifts between power plants, necessary to reach the most cost-effective outcome, may result in adverse effects concerning GHG emissions.

3.3. Impact of a CO_2 price

If a sufficiently high European Union emission allowance (EUA) price is introduced in the system, the major effect will be the switch in merit order between gas- and coal-fired power plants. Whereas, without any EUA, coal-fired power plants have the edge from an economical point of view, the outcome changes for increasing amounts of EUA costs, eventually leading to coal-power plants becoming relatively more expensive than gas-fired plants. The gas-fired plants of the efficient type, such as the modern combined cycle power plants, will be the first ones to outperform coal-power plants in terms of total cost, taking both fuel and emission costs into account.

The main impact of a switch between coal- and gas-fired power plants is the coal-fired power plants becoming the marginal plants

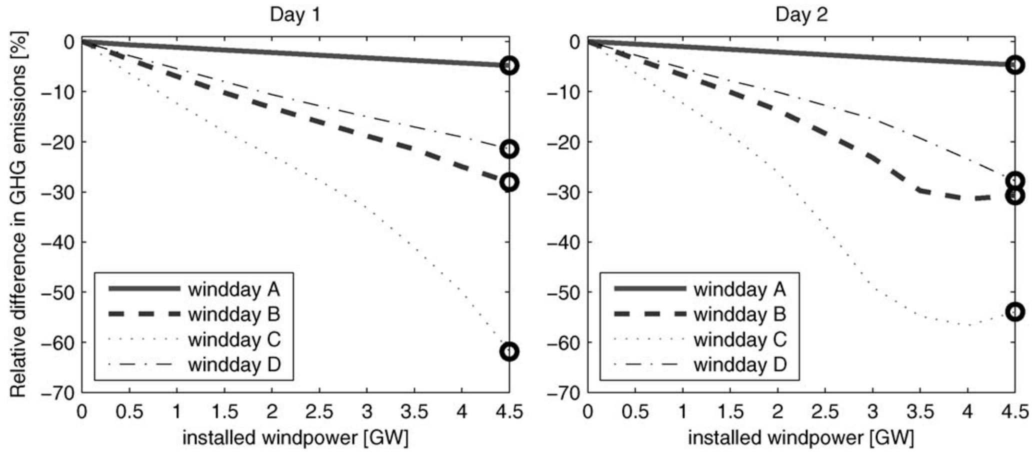

Fig. 8. GHG emissions reduction for demand profiles, *Day 1* and *Day 2*, each showing the impact of the 4 chosen wind speed profiles for increasing amounts of installed wind power in the Belgian system and with perfect forecast of the wind speed.

in the system. Therefore, for moderate amounts of wind power introduction, with coal-power plants remaining the marginal plants, the GHG emissions reduction effect of wind power will be even larger with the tax. On average however, coal-fired power plants do not remain the marginal power plants since for lower demand levels, most of the demand can be met with gas-fired power plants. In this situation, gas-fired plants become the marginal plant and will be the ones outperformed by wind power. Since at this point wind power replaces gas- instead of coal-fired plants, lower GHG emissions reductions are achieved than before the EUA introduction.

4. Technical upper limits for wind power

After having analysed the impact of large amounts of installed wind power on cost and GHG emissions, the focus is set on the technical barriers that the integration of wind power meets. Electricity generation systems have to be able to cope with the changes wind power induces. In some situations, very large amounts of wind power are faced with technical limitations. The impacts of a perfect and erroneous forecast are investigated in this section. The sign of the forecast error, referring to a positive or negative forecast error, has significant consequences for the type of encountered technical barriers.

4.1. Perfect forecast of wind power

When the actual wind power output is perfectly known during the UC period, the operation of the system experiences practically no hinder from the wind power integration. The power plants can be switched on and off according to the most optimal schedule so that supply and demand are balanced at all times.

4.2. Positive forecast error applied to wind power

In a second analysis, the system operation is studied with the possibility of a positive forecast error on the wind speed prediction and ensuing wind power output, referring to wind power output being overestimated. During the Unit Commitment (UC) phase, a certain amount of electricity from wind power is foreseen, based on the forecasted wind speed. Afterwards, in the dispatch phase, the actual wind speed can diverge from the forecast, leading to necessary adaptations in the system on the short-term. Depending on the activated power plants, the system will adapt to the actual wind power situation.

The ramp rates, minimal operation points, partial load efficiencies and minimal up- and down-times of the power plants constitute the most important characteristics in the capacity of the system to integrate the wind power output with its forecast errors into the operation of the system. The power plants that were activated during the UC phase and that are available through fast start up may prove to insufficiently cover the gap between forecasted and actual wind speed value. For large absolute amounts of positive forecast error, the current operation of the Belgian system might prove to be insufficient.

When a consistent positive 2 m/s wind speed forecasting error is set, problems during dispatch already occur with the high load profile of *Day 1*, as displayed in Fig. 9. Several elements come into play when forecast errors are made.

Firstly, the overestimation of wind energy needs to be balanced by the active power plants in the system. An amount of "spinning reserves" is required at all times, which is taken into account by a minimum amount of available, i.e. standby, capacity in the system for every hour. These reserves can be used to meet discrepancies between demand and supply. Sometimes however, more reserve capacity than minimally set is available, mostly in situations with low demand and corresponding many power plants operating at partial load, offering more options in terms of reserve provision. That is the main reason why the fewest technical barriers are reached in *Day 4*.

A second logical element is the absolute level of the forecast error. With large absolute forecast errors, more effort is needed for balancing the system again. This is also obvious when observing Fig. 9. Problems with forecast errors occur most frequently for the combination of relatively high levels of installed wind power capacity with the occurrence of high wind speed profiles. In this case *winddays B* and *D* lead to the largest technical barriers. The same exercise for a positive 1 m/s forecast error learns that the limits of wind power integration in the system are situated at a higher level, in these particular cases resulting in no technical barrier to be found for a 1 m/s positive error.

An exception to the above is true for *Windday C*. The reason is to be found in the shape of the power curve of the wind turbine, which defines how much wind speed corresponds to a certain amount of wind power. Not only the absolute level of wind speed plays a role in the impact of a forecast error, but the actual shape of the power curve is also an important element to consider. Since the transformation function of wind speed to energy is a cubic equation, the impact of an erroneous forecast is highest in the middle regions of the power curve, typically for wind speeds

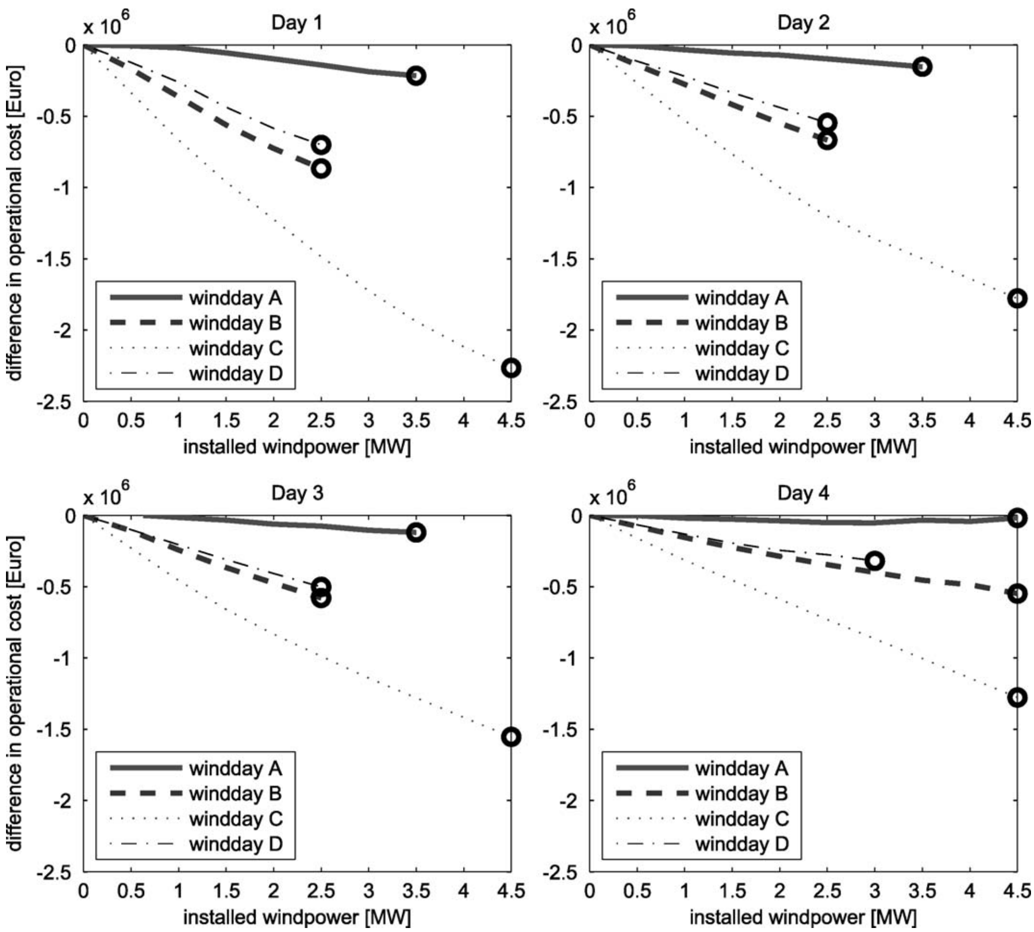

Fig. 9. The cost savings for 4 different decreasing demand profiles, *Days 1–4*, each showing the impact of the 4 chosen wind speed profiles for increasing amounts of installed wind power in the Belgian system. A positive forecast error of 2 m/s is used. The circles show where the system is not able to cope with the forecast error anymore. The operational cost savings relate to a situation without any wind power in the system and are expressed as negative costs.

between 5 and 12 m/s, as apparent in Fig. 2 [34]. That is the reason why *Windday C*, which has wind speed values around the rated wind speed of the turbine, experiences less difficulties in coping with the forecast error. The same absolute wind speed forecast error results in relatively smaller forecast errors expressed in terms of wind power output for the wind speed profiles *Windday B* and *D*. The profiles *B* and *D* are situated in the steepest part of the power curve and experience the largest impact in terms of absolute wind power changes for the same amount of wind speed error.

4.3. Negative forecast error applied to wind power

A negative forecast error, where a significant amount of wind power is unexpectedly delivered, can cause a situation of overproduction. In some cases, the system cannot adapt fast enough to this situation and electricity from wind power needs to be curtailed. In the following sections, both the situations with and without curtailment of wind power are investigated.

4.3.1. Without curtailment of wind power

In a situation where no curtailment of wind power is possible a situation of overproduction from wind power can arise. Since both large amounts of wind power and large absolute forecast errors are considered, many demand–supply imbalances occur that cannot be met by the available capacity in the system.

Fig. 10 shows the effect of negative forecast errors with a standard deviation of 2 m/s on the integration of electricity generated from wind power. Since no curtailment of wind power is foreseen, some situations might see the system not being able to cope with certain amounts of wind energy that need to be absorbed. This then results in difficulties to balance demand and supply.

The ability of electricity generation systems to absorb the overproduction in wind energy depends to a large extent on how much the active power plants can still lower their output regime. Power plants operating at full load might have to switch to partial load. Problems however occur at times of low demand during the day when a great share of power plants are already operating at partial load. The system then cannot always lower its electricity output in such extent that the extra wind energy can be taken in.

The reason for *Windday C* facing most difficulties is to be found in the average wind speed already being very high so that the unexpected 2 m/s increase does put more stress on the system, which has to absorb all the extra energy. This is more difficult for a system which already has to significantly adapt its output to the massive amounts of wind power.

The real problems start for lower demand profiles. These coincide with many power plants already operating at partial load. Therefore, with large amounts of unexpected wind energy to be absorbed by the system, more difficulties arise in those events where the load level of the active power plants cannot be lowered much more. This is most obvious for *Day 4* in Fig. 10.

4.3.2. With curtailment of wind power

When excess wind power output can be curtailed, fewer problems arise in terms of power plants being able to absorb the additional energy. Whenever a negative forecast error is made, the

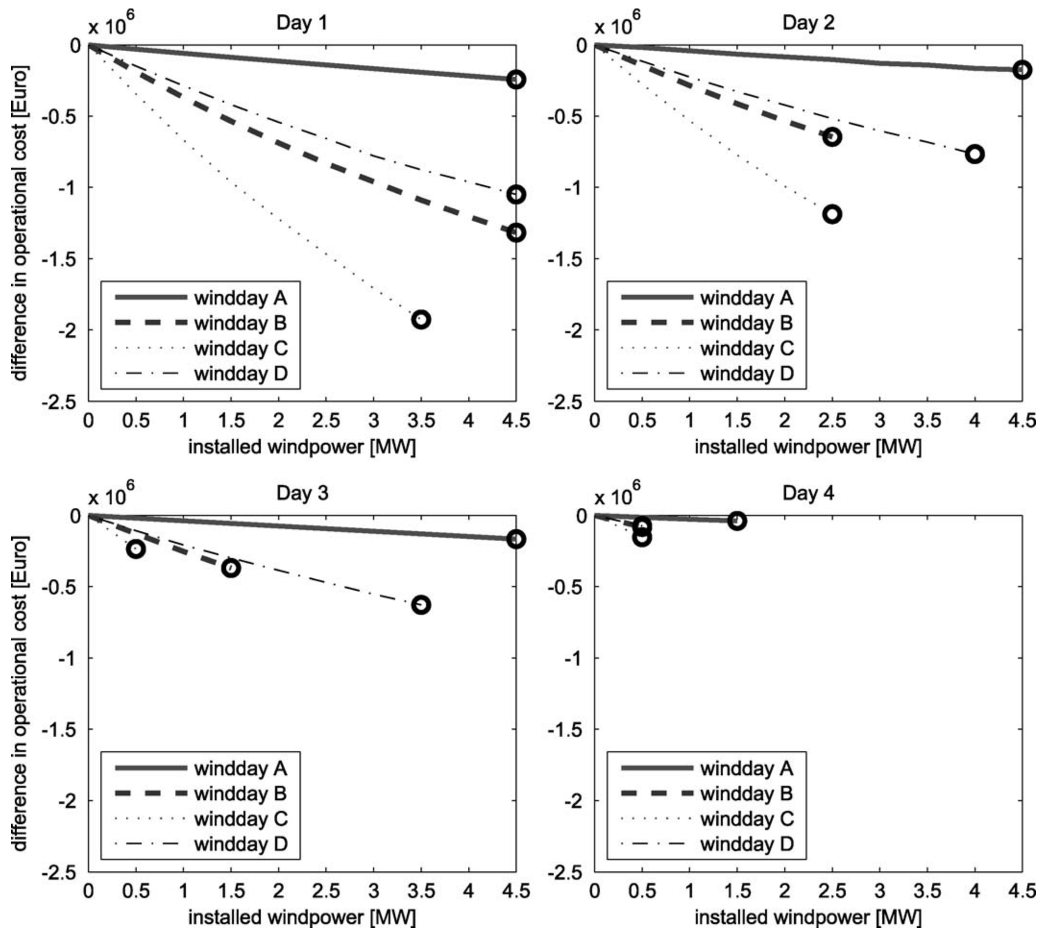

Fig. 10. The cost savings for 4 different decreasing demand profiles, *Days 1–4*, each showing the impact of the 4 chosen wind speed profiles for increasing amounts of installed wind power in the Belgian system. A negative forecast error of 2 m/s is used. The circles show where the system is not able to cope with the forecast error anymore. The operational cost savings relate to a situation without any wind power in the system and are expressed as negative costs.

additional wind energy can always be curtailed if the system is not able to cope with a sudden change. This severely reduces the technical barriers the model is faced with when a negative forecast error is made. For positive forecast errors, curtailment would offer no additional relief. For negative forecast errors however, the curtailment of some of the electricity from wind power can present a solution where the system previously could not cope with the uncertainty. This is most apparent when considering that the technical barriers faced with in Fig. 10 disappear with the possibility of curtailing electricity.

The amount of wind energy that needs to be curtailed varies according to the chosen variables. Logically, more wind energy output increases the probability of curtailment becoming necessary. More wind that needs to be absorbed by the system leads to more potential problems. Another, even more important, parameter is the demand profile. Lower profiles have more difficulties integrating all of the produced wind energy. It is not surprising the largest curtailments indeed occur for combinations of low overall demand with high levels of generated wind energy on the same moments as the demand lows. The combination of the four demand and wind speed profiles is represented in Table 1.

Table 1
Amount of wind energy curtailed in 24 h for every combination of demand and wind speed profile, in MWh. A negative forecast error of 2 m/s is used on an installed capacity of 3000 MW wind power.

	Windday A	Windday B	Windday C	Windday D
Day 1	0	0	0	0
Day 2	0	32	1183	0
Day 3	0	3736	4392	0
Day 4	335	7796	2799	7020

5. Conclusion

Wind power integration in Belgium entails considerable impacts on the Belgian electricity generation system. This is apparent on different levels.

First of all, the integration of wind power in a system usually leads to a decrease in operational costs. This is apparent in the performed simulations. However, when forecast errors are introduced, the system is not operated optimally anymore and situations can occur where large shares of these costs savings are lost on necessary adjustments of the system to the forecast errors.

The amount of wind power that can be incorporated in the Belgian system is not endless. Technical limitations exist which are linked to the operational characteristics of every power plant in the system as well as the fuel costs. On the adequacy side, it is important to invest in the Belgian system so that it remains reliable. The integration of wind power should not lower the reliability indices such as the LOLE. Looking at the short-term perspective, the technical limitations depend on the extent of forecast error that is foreseen. Both negative and positive forecast errors trigger possible technical limitations on the system integration. When allowing curtailment of wind power, the negative forecast error does not prove to be a technical challenge anymore, albeit that considerable opportunity costs can be suffered.

Another benefit of wind power is the reduction of greenhouse gas emissions. Combined with an emission allowance system, large amounts of emissions can be avoided.

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